

## **STATEMENT OF WORK**

### **COMPUTATIONAL AEROACOUSTIC ANALYSIS OF WIND TURBINES**

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## Background

Until recently, wind turbine manufacturers and operators were challenged by the task of keeping machines operating reliably. Next in order of importance were efforts to improve energy capture. Indeed, dramatic improvements have been made in both areas. There have been occasions, however, when acoustic imissions proved so vexing as to overshadow performance and reliability issues. Some of the early NASA-developed turbines consumed extensive resources in dealing with noise, including low-frequency impulsive imissions that have discredited downwind turbines ever since. Heated controversy about noise accompanied the siting of numerous projects in southern California. Small wind turbines suffer an unfavorable reputation for noise problems associated with high tip speeds, furling and flutter.

Wind turbine noise in the U.S. has been a problem only in isolated situations, and it is common to hear manufacturers dismiss the issue by speculating it will not be a problem in the sparsely populated Midwest. NREL cannot embrace this logic, because of the potentially damaging consequences of an error in judgment. Rather than ignore the issue, it is better to be proactive and develop the tools our industry partners need to avert problems.

DOE and NREL have initiated an important Low Wind Speed Turbine (LWT) development project focused on reducing the cost-of-energy at low and moderate wind sites. Recent analyses have shown that this effort, if successful, will admit significantly more wind resources in close proximity to load centers and transmission lines. In this circumstance, it is essential that the turbines available for deployment are quiet. This suggests there should be an effort by NREL to measure the acoustic signature of existing turbines and work diligently to reduce (below the state of the art) the signatures of new turbines developed under the LWT project. Coincidentally, with recent energy shortages and the ensuing statewide deployment incentives, there is resurgent interest in small wind turbines for distributed generation. Because of the potential for siting near residences, noise may be even more important for small turbines than for large turbines installed in wind power plants.

The primary sources of wind-turbine aeroacoustic noise are inflow turbulence, flow separation, trailing-edge bluntness, boundary-layer trailing-edge interaction, and the blade-tip vortex. Trailing-edge noise is the dominant mechanism that must be controlled if truly quiet wind turbines are desired. Fortunately, wind tunnel tests of low noise airfoils designed by a European consortium show the potential for appreciable reductions in acoustic imissions. Similar design efforts are underway at NREL. It is not clear if these anticipated improvements will materialize in field tests of real wind turbines with typical blade tip shapes. The least understood mechanism is blade tip noise, which originates from the tip vortex. It is not certain by what mechanism this noise is produced and how egregious it is compared to trailing edge noise from the remainder of the blade. There is speculation that reductions of 2-3 dBA can also be obtained by judicious tip treatment. Consequently, it appears there is an opportunity for the NREL aeroacoustics research program to have an important impact by facilitating reductions in trailing edge and blade tip noise. Other opportunities exist in the establishment of reliable wind tunnel and field-test databases and the development of computational methods for future aeroacoustic analyses.

The development of computational aeroacoustic (CAA) codes that provide meaningful insight into the wind turbine aeroacoustic problem will not be a short-term effort. The success of the acoustic analysis will depend upon the accuracy with which the fundamental flow field can be modeled. And there is ample evidence that for wind turbine rotors, this is very difficult, indeed, owing to the turbulent, unsteady, three-dimensional nature of the flow. Nevertheless, the process of developing the CAA models must begin, with the expectation that both physical insight and computational methods will improve over time.

## **GOALS AND OBJECTIVE**

The goals of this project are to develop a thorough understanding of the mechanisms for generation, propagation, and mitigation of wind-turbine-blade acoustic emissions; to document and disseminate this information in the form of NREL reports, technical papers, seminars and colloquia; and to support the U.S. wind industry in applying rational acoustic-design principles to the development and deployment of advanced wind turbines. The specific objective is to develop computational aeroacoustic codes to analyze wind turbine blade noise sources as impacted by important configuration variables.

## **SCOPE OF WORK**

This statement of work calls for the Subcontractor to begin by conducting a literature search and review of previous research on wind turbine aerodynamics and aeroacoustics. Subsequently, a computational approach will be formulated to address the specific aeroacoustic problem identified in the Subcontractors proposal. A description of the computational model, expected results, project work plan, anticipated schedule and budget will be presented to an NREL review team. With NREL approval, the model will be implemented and validated by applying it to applicable experimental data. The project will conclude with the submission of a final report and presentation of a final project review meeting.

## **WORK TASKS**

### **Task 1      Review of Previous Research**

NREL expects the Subcontractor to have appropriate experience in computational aeroacoustics, but not necessarily to have complementary experience in wind turbine aerodynamics. Wind turbines blades are immersed in an unsteady, sheared flow, and their behavior is further complicated by rotational dynamics and potential blade-tower wake interactions. Success in the development of CAA codes will necessitate a familiarity with these issues and with previous attempts to solve both aerodynamic and aeroacoustic problems. Fortunately, there is a large body of literature that documents these important efforts. For the last two decades, the laboratories of the National Aeronautics and Space Administration (NASA) and various affiliates have conducted high-quality research on airfoil aeroacoustics, as well as specialized studies of wind turbine noise. Furthermore, considerable work has been done over the last decade by research consortia under the sponsorship of the European Commission. It is imperative that the Subcontractor is familiar with this body of work to determine how it may be used to advantage in formulating its computational approach. Therefore, in Task 1, the Subcontractor shall conduct a thorough review of the prior research related to wind turbine aeroacoustics and the CAA problem. In addition, to accelerate its familiarity with contemporary wind turbine engineering issues, one or more of its representatives shall attend the American Society of Mechanical Engineers (ASME) Wind Energy Symposium to be held in conjunction with the American Institute of Aeronautics and Astronautics (AIAA) Aerospace Sciences Meeting in Reno, Nevada in January 2003. The goal of Task 1 is for the Subcontractor to become familiar with previous wind turbine aerodynamic and aeroacoustic research, both successful and unsuccessful. In doing so, the Subcontractor should be better able to define a robust physical model and formulate an efficient computational approach to the problem it has chosen to investigate.

### **Task 2      Formulation of Computational Approach**

The Subcontractor shall expand and refine its proposed computational approach for modeling the flow field, blade geometry, rotor wake, and if appropriate, wind turbine tower. For simpler problems, such as two-dimensional airfoil shapes, modeling of the tower and three-dimensional blade planform will not be necessary. The chosen computational approach, in terms of mesh design, boundary conditions, unsteady loading and noise radiation, will depend upon the specific problem addressed. Estimates shall be made of the number of variables, number of grid points and required computation time. The desired results include noise intensity, acoustic spectra and directivity as a function of important independent variables,

such as airfoil shapes, blade geometry, mean wind speed, inflow turbulence and rotor rotational speed. At the conclusion of this task, the Subcontractor shall be able to define the problem in detail and completely describe the solution approach it proposes to follow.

### **Task 3 Interim Report**

### **Deliverable #1**

In Task 3, the Subcontractor shall prepare an Interim Report (Deliverable #1) that describes the work performed to date. It shall summarize the literature search conducted in Task 1, including the chronological progression of research and pertinent results. A description of the computational formulation and expected results developed in Task 2 shall also be provided. In addition to this technical description, the Subcontractor shall develop a Project Work Plan that includes all of the details important to the subcontract effort and expands upon its proposed approach. The purpose of this plan is to ensure that all of the important work elements have been considered, including an itemized work breakdown structure, the manner in which tasks will be sequenced, the personnel and other resources that will be required, and the measures of merit by which progress will be judged. The plan shall include suggestions for empirical data required for validation of the CAA codes. This will assist NREL in developing programs to obtain these data if they do not already exist. Finally, the plan shall include a budget for the remainder of the project and a schedule of important events and milestones in the form of a bar chart. Although the Subcontractor is free to propose a work plan that suits its own preference, NREL will require a logical, systematic engineering approach that is likely to result in the achievement of the project objectives.

In large part, the information contained in the Interim Report will be used to determine if the proposed approach has sufficient merit to warrant continuation of the project. Therefore, it should be sufficiently complete, clear, and concise to permit evaluation by a team of knowledgeable professionals. The format of the Interim Report shall be developed in cooperation with the NREL Project Manager, and a draft version shall be submitted for review. The Subcontractor shall make appropriate revisions to the report in accordance with recommendations made by the NREL Project Manager.

### **Task 4 Interim Project Review Meeting**

### **Deliverable #2; Meeting #1**

The Subcontractor shall conduct an Interim Project Review Meeting (Meeting #2) at NREL to discuss the proposed approach for developing and validating the CAA codes. The meeting shall be attended by important members of the Subcontractor's team and the NREL Technical Review Team. The Subcontractor or key members of its team shall present information that addresses the following topics.

- project status, including changes since last review,
- summary of literature search, including pertinent results of previous research,
- proposed computational approach, including:
  - rationale for major features,
  - techniques and sequence of analysis,
  - anticipated computational effort, and
  - expected results,
- proposed validation approach, including:
  - required empirical data,
  - anticipated analysis methods,
  - expected results, and
  - measures by which success will be judged,
- discussion of team members including qualifications, roles and responsibilities,
- anticipated schedule showing key milestones and deliverables,
- anticipated cost by task and year.

To allow sufficient preparation time, multiple copies of an Interim Project Review Package (Deliverable #2) summarizing this material shall be provided to NREL at least three weeks in advance of the meeting.

*After the Interim Report and Interim Project Review Package have been delivered and the Interim Project Review Meeting has been conducted, NREL will evaluate the project (Critical Project Review) and decide whether or not to proceed. This decision will be based upon technical accomplishments and programmatic issues. If a decision is made to proceed, the Subcontractor shall advance to the next work task. If a decision is made not to proceed, the Subcontractor shall continue to work only on final reporting and administrative details required to conclude the subcontract. In general, performance of the subcontract beyond Task 4, and the attendant expenditure of funds, shall not proceed until NREL approval is received to do so after the Critical Project Review. If the Subcontractor wishes to commit resources to work beyond Task 4 before the Critical Project Review is successfully completed, it must make a formal request to the NREL Project Manager and receive authorization before proceeding.*

#### **Task 5      CAA Code Development**

#### **Deliverable # 3**

The Subcontractor shall implement the computational approach developed in Task 2 and approved by NREL for development. The resulting CAA Codes (Deliverable #3) shall be checked for error free operation and documented so that input data methods and output data formats are readily understandable by NREL research staff. The Subcontractor shall endeavor to develop the code(s) for installation on the NREL IBM SP parallel computer. This system has forty-eight Power 3 processors configured as twelve 4-processor nodes. Each node has two gigabytes of shared memory. Applications developed to use MPI on distributed memory computers should be able to run on this system with only minor modification. *Compatibility of the developed CAA code(s) with this computer is not an absolute requirement of the subcontract, but if the codes are compatible, the Subcontractor shall provide support for installing, operating and de-bugging them at the NREL facility.*

#### **Task 6      CAA Code Validation**

An important element of the project is to determine how accurately the code(s) predict – in both a relative and an absolute sense – the acoustic imissions for one or more benchmark problems. NREL has experimental data in the form of measured sound pressure level (including spectral data) for various airfoils and for several wind turbine configurations and wind speeds. It is understood, however, that it may be necessary to obtain other data for the specific purpose of validating the CAA methods developed in this project. Assuming that suitable data are available in the literature, or will be obtained by NREL through new experiments, the Subcontractor shall use this information to validate the code(s) developed in Task 5. An effort shall be made to explain any discrepancies between the measured and predicted acoustic fields, and if possible, to make corrections to bring the code(s) in closer agreement with experimental results.

#### **Task 7      Final Report**

#### **Deliverable # 4**

The Subcontractor shall prepare a Final Report (Deliverable #4) describing the entire project. The content, format and style shall be suitable for publication as an NREL subcontract report. To the extent necessary, the report shall evolve through a series of revised drafts until the NREL Project Manager approves a final version.

#### **Task 8      Final Project Review Meeting**

#### **Deliverable #5; Meeting #2**

The Subcontractor shall conduct a Final Project Review Meeting (Meeting # 2) at NREL in Golden, Colorado, as specified in the subcontract schedule. At this meeting, which shall be attended by the Subcontractor and important members of its project team, the contents of the Final Report shall be presented along with answers to questions previously posed by the NREL review team. To allow sufficient preparation time, multiple copies of a Final Project Review Package (Deliverable #5) summarizing this material shall be provided to NREL at least three weeks in advance of the meeting.

## **REPORTING REQUIREMENTS**

### **Distribution**

The Subcontractor shall send to the NREL Project Manager one unbound paper copy and an electronic file of all draft deliverables submitted for review. After revision and final approval, an electronic file shall be sent to the NREL Project Manager and the NREL Subcontract Administrator. Acceptable formats for electronic files are Word and WordPerfect. Note the special requirements described below under "Deliverables." The addresses for delivery of reports and other correspondence are shown below.

National Renewable Energy Laboratory  
National Wind Technology Center  
1617 Cole Boulevard, MS3811  
Golden, CO 80401  
Attention: Neil Wikstrom

National Renewable Energy Laboratory  
National Wind Technology Center  
1617 Cole Boulevard, MS3811  
Golden, CO 80401  
Attention: (Project Manager to be determined)

### **Report Quality**

Engineered products of high quality require engineering documentation of high quality. Therefore, the reports required under this subcontract are expected to comply with high standards for technical writing. These standards include logical organization, consistent formatting, completeness, conciseness, preciseness and grammatical correctness. To achieve this level of quality, the Subcontractor should plan, if necessary, to supplement its staff with consultants who are experts in the technical writing of engineering reports. The "Style Guide for NREL Subcontract Reports" is an example of acceptable style. Alternative styles and formats may be acceptable to NREL, if they meet the desired standards for quality.

### **Deliverables**

The Subcontractor shall submit the following deliverables in accordance with the Statement of Work. Deliverables indicated with an asterisk (\*) must comply with the Electronic Reporting Requirements described in Attachment B.

1. Interim Report
2. Interim Project Review Package
3. Computational Aeroacoustic Code
4. Final Report\*
5. Final Project Review Package

### **Meetings**

The Subcontractor shall conduct the following meetings in accordance with the Statement of Work. In addition to these formal meetings, informal review meetings shall be conducted at the request of the NREL Project Manager or the Subcontractor.

1. Interim Project Review Meeting
2. Final Project Review Meeting

### **DOE/NREL Subcontractor Reviews**

The Subcontractor shall attend the DOE/NREL Subcontractor Review Meeting in each year the subcontract is in place. At these meetings, which are held in Golden, Colorado, the Subcontractor shall report on the status of the subcontract and the significant project results.

## **Quarterly Reports**

At the end of each calendar quarter, the Subcontractor shall submit brief reports that document the progress its team has made toward completion of the project. Each report shall be approximately five pages in length and prepared in accordance with the format provided in Attachment E. Reports shall be submitted to the NREL Subcontract Administrator and the NREL Project Manager via electronic mail in a Microsoft Word electronic format. They shall be delivered to NREL within fifteen (15) days of the end of each calendar quarter. The Subcontractor shall identify the reports as deliverables with the company name, subcontract title and subcontract number clearly identified.

Quarterly reports shall focus on accomplishments since the last report; problems or variances from planned activity, the completion of milestones, deliverables, meetings or other achievements. They shall provide a summary labor report, cost report and schedule. The information shall be presented as follows.

- a summary of significant events occurring since the last report presented as a “bulleted” list of sentences or short paragraphs, and including (i) a statement of the percent complete for the project in comparison to the percent of the planned labor hours expended, and (ii) a statement of the cumulative costs for the project in comparison to the total authorized costs for the subcontract,
- a summary of analysis and test support provided by NREL since the last report,
- the outlook for the next quarter presented as a “bulleted” list of anticipated significant events,
- a tabular summary of labor hours showing the task number and name, planned labor-hours, percent complete, earned labor-hours, actual (cumulative) labor-hours, percent of the planned labor hours expended and the sum of each of the labor-hour columns,
- a tabular summary of subcontract costs (using the same cost categories as the Subcontractor’s Cost Proposal Form) for the report period and the cumulative costs for the subcontract, and
- a one-page, updated project schedule in bar-chart format, as originally supplied in the Project Work Plan, showing the percent complete for each project activity.

## **Information for Public Distribution**

Some data produced under the subcontract will be available for dissemination to the public without restriction. Potential uses of the data include journal and magazine articles, conference papers, promotional brochures and audio-visual presentations describing the Subcontractor’s project, or the wind energy program and its accomplishments. In these situations, the Subcontractor shall make a timely response in providing text, sketches, drawings, photographs and other descriptions of work performed under the Subcontract. The information shall be accompanied by permission to use the photographs and images in an unrestricted manner, including placement on the Internet.

## **Critical Project Reviews**

NREL will continually evaluate its research portfolio. Therefore, Critical Project Reviews will be held periodically to determine the appropriate scope of work and level of support for various projects. This decision will be based upon technical accomplishments and programmatic issues. If a decision is made to proceed as planned, the Subcontractor shall advance to the next work activity. If a decision is made not to proceed, the Subcontractor shall continue to work only on final reporting. In general, performance of the subcontract and the attendant expenditures shall not proceed until NREL approval is received to do so after Critical Project Reviews. If the Subcontractor wishes to commit resources to long lead items before a Critical Project Review is successfully completed, it must make a formal request to the NREL Project Manager and receive authorization before proceeding.

The timing and nature of Critical Project Reviews may vary from one subcontract to another. However, for planning purposes, the Subcontractor shall anticipate that these reviews will occur annually.

**ATTACHMENT A**  
**QUARTERLY REPORT FORMAT**

**SUBCONTRACTOR NAME**  
**COMPUTATIONAL ANALYSIS OF WIND TURBINE AEROACOUSTICS**

**Subcontract No. AAA-xxx-yyy-zz**

NREL Project Manager: (To Be Determined)  
NREL Subcontract Administrator: Neil Wikstrom

**Major Accomplishments for the \_\_\_\_\_ Quarter 2003**

- .....
- .....
- At the end of this month xx.x% of the project had been completed with yy.y% of the planned labor hours expended.
- Cumulative costs to date have been \$xxx,xxx (\$yyy,yyy = total subcontract)

**NREL Analysis and Testing Support**

- .....
- .....
- .....
- .....

**Outlook for the Next Two Months**

- .....
- .....
- .....
- .....

**Table 1 and Table 2 (Attached)**



**Table 1 - Tabular Labor Summary**

WBS Number/Name (example shown below)	Planned Labor Hours <sup>1</sup>	Percent Complete <sup>2</sup>	Earned Labor Hours <sup>3</sup>	Actual Labor Hours <sup>4</sup>	Percent Expended <sup>5</sup>
1. Review of Previous Re- search					
2. Computational Formulation					
3. Interim Report					
4. Interim Project Review Meeting					
5. CAA Code Development					
6. CAA Code Validation					
7. Final Report					
8. Final Project Review Meeting					
Total		(xx.xx) <sup>6</sup>			(yy.yy) <sup>7</sup>

- <sup>1</sup>. From the Project Work Plan. Planned labor hours, which include lower-tier subcontractors and consultants, should not change after the Plan is approved by NREL.
- <sup>2</sup>. From pre-determined milestones or estimates of percent complete for each subtask.
- <sup>3</sup>. Computed as the product of planned labor hours and percent complete: Column (1) x Column (2).
- <sup>4</sup>. Cumulative labor hours billed through this time period.
- <sup>5</sup>. Computed as the actual labor hours divided by the planned labor hours: Column (4) ÷ Column (1).
- <sup>6</sup>. Computed as the total earned labor hours divided by the total planned labor hours.
- <sup>7</sup>. Computed as the total actual labor hours divided by the total planned labor hours.

**Table 2 - Tabular Cost Summary**

Cost Category	Month of	Cumulative
1. Direct Materials		
2. Material Overhead		
3. Direct Labor		
4. Labor Overhead & Fringe Benefits		
5. Equipment		
6. Travel		
7. Lower-Tier Subcontractors		
8. Consultants		
9. Other Direct Costs		
10. Total Direct Cost & Overhead		
11. General & Administrative Expense		
12. Facilities Capital Cost of Money		
13. Royalties		
14. Total Project Cost		
15. Subcontractor's Cost Share		
16. NREL's Cost Share		

## ATTACHMENT B

### ELECTRONIC REPORTING REQUIREMENTS

As set forth in Department of Energy Order 241.1A, NREL is required to submit in an electronic format all scientific and technical information, including subcontract report deliverables intended for public distribution, to the DOE Office of Scientific and Technical Information (OSTI). In addition, it is NREL's intention to post subcontract report deliverables containing publicly available information (e.g. non-confidential, non-protected, non-proprietary information) for distribution on the NREL Intranet or the Internet.

The NREL Subcontract Administrator and the NREL Technical Monitor shall determine which report deliverables are appropriate for submission and shall identify such report deliverables in the subcontract Statement of Work (SOW). The NREL Subcontract Administrator or Associate shall ensure that both the "hard copy(ies)" and the electronic version(s) of such report deliverables, identified in the subcontract Statement of Work and delivered by the Subcontractor in accordance with this Article, are sent to NREL Publication Services for subsequent distribution to OSTI.

The Subcontractor shall provide the final approved version of report deliverables intended for public distribution as specified in the subcontract Statement of Work in accordance with the following electronic reporting requirements:

- a. The Subcontractor shall submit all report deliverables intended for public distribution (including annual, or final reports) as electronic files, preferably with all graphics and images embedded within the document. As identified in the subcontract Statement of Work, the electronic files shall be submitted along with an accompanying hard (printed) copy(ies) of the report. Limited exceptions allowing some graphics and images to be submitted as hard copies only may be granted on a case-by-case basis. The exceptions process for graphics and images is described in Paragraph E below. It shall be made clear in the deliverable transmittal letter that certain graphics and images are supplied in hard copy only.
- b. All final approved version submissions shall be delivered to NREL on PC- or Macintosh-formatted media (3.5 inch disks, Zip and Jaz cartridges, or CD-ROM). Files of 1 Mb or less can be sent via e-mail to the 1) NREL Technical Monitor; and, 2) the NREL Subcontract Administrator or Associate (as specified in the Statement of Work).
- c. The preferred format is a single electronic file that includes all of the text, figures, illustrations, and high-resolution digital photographs (or photographs should be scanned and incorporated in the text). Acceptable file formats are:
  - \_ Microsoft Word (v.6.0 or newer for PC or Macintosh)
  - \_ WordPerfect (v.6.1 or newer for PC)
  - Microsoft PowerPoint
  - Microsoft Excel
- d. If it is not possible to include all of the graphics and images (figures, illustrations, and photographs) in the same file as the text, NREL will accept the text in one of the above formats and the graphics and images as separate electronic graphic or image files\*. The native files for any page layout formats submitted shall be supplied. The following software is supported on both Macintosh and PC platforms:

- QuarkXPress (.qxd)
- Pagemaker (.pm)
- Photoshop (.psd)
- Illustrator (.ai)
- Freehand (.fh)
- Corel Draw (.cdr)
- Framemaker (.fm)
- Microsoft Publisher (.pub)

\*The acceptable graphic or image file formats are: .eps, .tif, .gif, .jpg, .wpg, .wmf, .pct, .png, bmp, .psd, .ai, .fh, .cdr. The preferred resolution for graphics or images is 150 to 300 dpi. Include all fonts that were used in creating the file.

- e. In the rare case that the graphics or images cannot be supplied electronically, either incorporated within the text or as a separate electronic file, original hard copies will be accepted. The Subcontractor shall obtain prior approval from the Subcontract Administrator before submitting graphics or images in hard copies. It shall be made clear in the deliverable transmittal letter that certain graphics and images are supplied in hard copy only.
- f. For all calculations in support of subcontract reports that are conducted in ASPEN+, an electronic copy of INPUT, REPORT and BACKUP (if Model Manager is used) must be submitted with all reports. Additionally, if costing or sizing calculations are conducted in a spreadsheet [no process calculations (heat and material balances) in spreadsheet format are permitted], a copy of the fully documented MS Excel file shall be supplied. Note that vendor quotes and other non-original material can be supplied in hard copy.
- g. A fully executed release shall be supplied to NREL with all photographs, regardless of whether such photographs are delivered to NREL electronically or in hard copy. Such release shall certify that the National Renewable Energy Laboratory and the United States Government is granted a non-exclusive, paid-up, irrevocable, worldwide license to publish such photographs in any medium or reproduce such photographs or allow others to do so for United States Government purposes.
- h. The Subcontractor may contact NREL Publication Services at (303) 275-3644 with questions regarding technical guidance concerning the submission of subcontract report deliverables as electronic files or exceptions to electronic files for graphics and images.